IPST Technical Paper Series Number 546

Distribution of Mass Flows in Black Liquor Sprays

H.J. Empie, S. Lien, and D.B. Samuels

December 1994

Presented at the
AIChE Annual Meeting
November 15, 1994
San Francisco, California

For submission to AIChE Annual Mtg, Forest Products Div.:

DISTRIBUTION OF MASS FLOWS IN BLACK LIQUOR SPRAYS

by

H. Jeff Empie

Steven Lien

Douglas B. Samuels

Institute of Paper Science and Technology
Atlanta, Georgia 30318

Work Performed Under U.S. DOE Contract No. DE-FC02-88CE40839

November 15, 1994

ABSTRACT

Black liquor has been sprayed through standard splashplate and V-jet nozzles at typical nozzle conditions using an enclosed spray chamber. The sheets of liquor that issue from the nozzles have been characterized with respect to distribution of mass flows within the total spray angle. A maximum mass flux occurs at the spray centerline which coincides with the nozzle axis. The mass flux exhibits a parabolic dependence on angular position, decreasing in magnitude out to the edge of the sheet. At the very outer edge was a thick, slow-moving rim. Model predictions of the centerline flux and the full spray angle agree to within 10% of the experimental values for the splashplate nozzle. Results will be useful in modeling combustion processes in kraft recovery boilers where a detailed knowledge of the black liquor spray characteristics is required.

DISTRIBUTION OF MASS FLOWS IN BLACK LIQUOR SPRAYS

INTRODUCTION

An essential and valuable by-product of the kraft pulping process is black liquor, an aqueous solution of spent inorganic pulping chemicals and organic species extracted from the wood. Included in the organics are dissolved lignin and degraded carbohydrates. For economic and environmental reasons, kraft black liquor is put through a recovery process where the energy content provided by the organics is reclaimed in the form of process steam, and the inorganics are regenerated and recycled to the pulping operation. Typically, 95-97% of the inorganic chemicals are recovered, and the steam generated satisfies over 40% of a modern kraft mill's energy needs (1).

The most important unit operation employed in the recovery cycle of the kraft pulping process is combustion of black liquor in the recovery boiler. This step is initiated by spraying the concentrated liquor through one of several types of commercial nozzles, the most common being the splashplate, the V-jet, and the swirl cone. The liquor issues from the nozzle as a thin sheet, which subsequently breaks up into droplets. These droplets then go through the sequential processes of drying, pyrolysis and gasification, combustion, chemical reduction, and coalescence of the molten inorganic salts (2). The rates at which these physical and chemical processes occur are highly dependent upon the size and size distribution of the droplets formed from the spray. The smaller the droplet, the greater the surface area per unit mass of liquor and, hence, the greater the rates of heat and mass transfer between the liquor particles and the furnace gases. While this is desirable for increasing recovery boiler capacity, it is offset by higher entrainment and carry-over, which are characteristic of small particles in an upward flowing turbulent gas stream. Inevitably, the result is accelerated fouling of the relatively cool boiler tubes and more rapid plugging of the heat transfer section of the boiler.

To increase throughput while minimizing tube fouling and plugging rates, improved understanding and control of the liquor spraying step is needed. Not only are drop size and size distribution important in this regard, but also of concern is the spatial mass distribution of the liquor across the furnace cross-section. An uneven distribution could lead to localized regions of intense combustion and result in an unwanted hot spot. Such an occurrence can accelerate corrosion rates of the furnace walls and result in metal failure and premature shutdown.

The distribution of liquor within the furnace firing zone is not known and will not be in the near future because of the extreme difficulty of taking measurements in this turbulent, particulate-laden, corrosive, inaccessible, high temperature region. Characterization is best achieved through mathematical modeling using computational fluid dynamics and fundamental kinetic and transport rate data.

The key to successfully modeling the recovery boiler furnace zone is by starting with an accurate understanding of black liquor nozzle performance. Drop size and size distribution data are of course paramount. With regard to spatial distribution, it is also important to know not only the total angle of the spray sheet produced initially by a given nozzle and liquor flow conditions, but also how the mass flow of black liquor varies with the angular position within the sheet. Data are reported below on the mass flow distribution of liquor sprays from two different commercial nozzles, the Babcock & Wilcox (B&W) 12/45 splashplate and the Spraying Systems (SS) V-jet 11/65.

EXPERIMENTAL

Black liquor was sprayed continuously through the B&W splashplate and SS V-jet nozzles using a heated, recirculating pump-around loop system (cf. Fig. 1). The central component of the system was a spray chamber which served the dual purpose of providing a visible spray pattern while containing and storing the liquor inventory. The stainless steel chamber was 2.1 m long, 1.8 m deep, and 3.0 m high with a V-shaped, heated bottom section that could store up to 1100 liters of liquor at temperatures up to 100°C. The front and rear walls contained 1.5 m x 1.2 m tempered glass windows to allow backlighting and videotaping of the liquor spray sheet and droplets. The side of the chamber had an opening for the spray nozzle which was oriented to deliver the liquor sheet in a horizontal trajectory. (When videotaping to get drop size measurements, the liquor sheet is oriented parallel to the windows.)

A two-stage Moyno pump circulated the liquor from the spray chamber through a spiral heat exchanger, which could raise the liquor temperature by 20°C at 190 l/min, then through a Brookfield viscometer and back to the chamber. When the liquor was at the desired conditions for testing, the bypass loop was closed and the flow directed through the nozzle. The system had the capacity to deliver up to 150 l/min (as measured by a Foxboro magnetic flowmeter) of liquor to the nozzle at 550 kPa (80 psi). A continuous water addition line was included in the pump-around loop to replace any water vapor which escaped from the hot liquor spray, thereby maintaining a constant liquor solids content. Because of odor control considerations, the spray chamber was operated under a slight negative draft. An ID fan drew air in through eight adjustable dampers, after which this gas flow plus

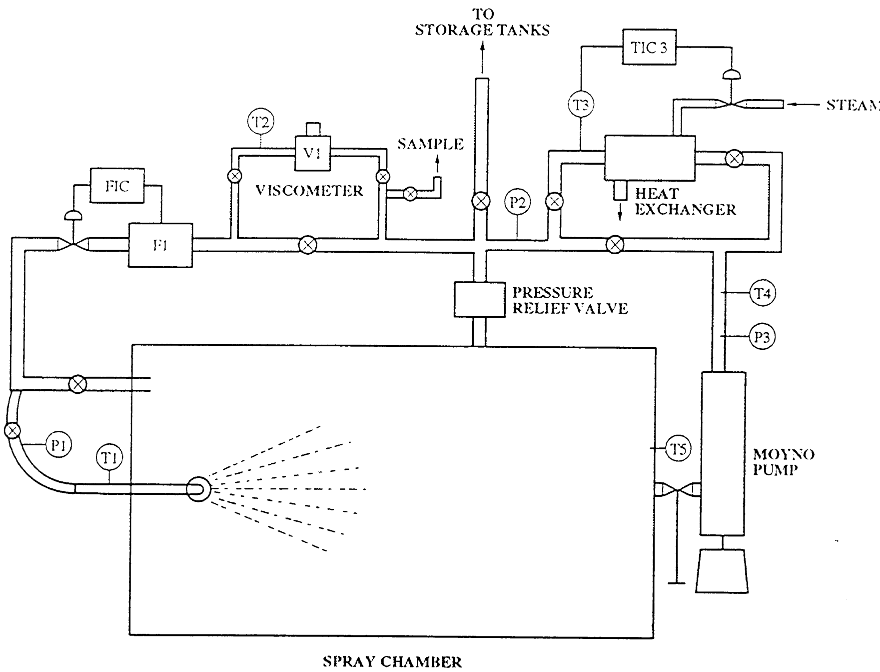

Fig. 1 - Schematic of Black Liquor Spray System

any volatiles coming from the liquor spray were pulled through a carbon absorber (provided by Westvaco Corp.) before being exhausted to the atmosphere.

The two nozzles used in this work were a B&W 12/45 splashplate (Fig. 2) and a SS 11/65 V-jet (Fig. 3). Splashplate-type nozzles are widely used for black liquor spraying. They feature a straight tapered nozzle section which causes the black liquor flow to impinge on a flat plate oriented at angles to the nozzle axis ranging from 35° to 55° (in this case 45°). The first two digits in the nozzle designation (i.e., 12) refer to the nozzle exit diameter in thirty-seconds of an inch. In the SS V-jet designation, the first two digits are again the exit diameter in 32^{nds} of an inch; the second two digits represent the total spray angle of the sheet of liquor issuing from the nozzle.

Samples of sprayed liquor were collected by using two different types of patternators. The first arrangement used a single box with a large 7.6 x 7.6-cm. opening. A trap door on the front of the box could be opened for a fixed length of time (generally, 5 to 10 seconds) and then quickly closed. This was used with the SS V-jet nozzle, where samples were collected at a distance of about 84 cm. from the nozzle.

A second patternator was constructed for the B&W splashplate nozzle. Nine 2.5 x 2.5-cm. sampling boxes were arranged on a semicircular frame at 20° intervals. The radial distance from the nozzle to the front edge of each box was fixed at 11.5 cm. The sampling boxes cut the liquor sheet into sections which could

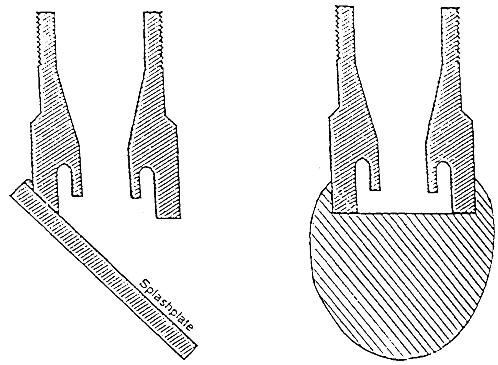

Fig. 2 Splashplate Nozzle

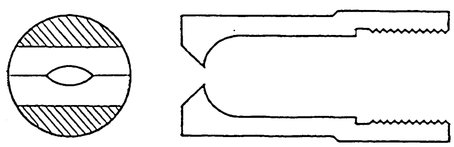

Fig. 3 V-jet Nozzle

be collected simultaneously for a fixed time and accurately weighed to determine the mass flow rate at the nine different angles. Because the angle and position of the sampler were fixed with respect to the nozzle, these samples were slightly more reproducible than those collected with the larger single-box sampling device, which had to be repositioned for each sample.

For each data point, two to four samples at each angular position were collected and averaged. Measurements over the total spray angle were taken at five points for the SS V-jet and nine for the B&W 12/45 splashplate. The test conditions are listed below in Table 1. In all cases at a given spray angle the entire liquor sheet in the direction perpendicular to the sheet surface was collected.

This work was done at relatively low solids concentrations (55% to 65%), which allowed the experiments to be performed at lower temperatures (50°C to 85°C). This was an important safety consideration, since the experimental procedures for these tests required close physical access to the spray nozzle. Changes in solids concentration are not expected to have a large influence on the mass flux distribution.

Table 1 - Spray Angle for the Test Nozzles

Test No.	Nozzle	Liquor Viscosity (cP)	Nozzle Pressure (kPa)	Reynolds Number	Spray Angle (°)
30A	B&W 12/45	219	123	492	140
30B	"	229	239	684	170
31A	"	50	126	2697	150
31B	"	66	241	2862	166
28A	SS 11/65	55	75	2120	57
28B	"	68	137	2333	60
27A	"	346	76	321	40

Four tests were performed with the B&W 12/45 splashplate (Figs. 4-7), while three were done with the SS V-jet nozzle (Figs. 8-10). The spray angle (α) represents the angle bounded by the left and right outer edges of the spray sheet. The overall angle determinations were relatively inexact and have an estimated confidence limit of ± 10°. Right at the outer edge of the sheet there existed a rim of liquor that was thicker than the sheet just inside the rim. Hence, the mass flow just inside the spray angle was larger than expected, while just beyond it the flow was essentially zero.

The spray angle for the splashplate is much wider than for the V-jet and approaches 180° at high flow rates and low viscosities. The SS V-jet nozzle is classified as a 65° nozzle by the manufacturer, and the measured values do approach this value at high flows and low viscosities. The variation of the spray angle seen in these tests is typical behavior for pressure nozzles. The spray angle will increase with operating pressure until it reaches a maximum value; beyond this point the spray angle will decrease slightly with increasing pressure.

In order to quantify how the mass flow varies with angular position in the spray sheet, it is necessary to define a mass flow factor (MFF) as the ratio of the measured flow at a given angular position to the average flow over the total spray angle (3). Because each sampling box has a fixed width, the measured mass flow represents an average over the angle, $\Delta\theta$, where the position angle, θ, is defined as the angular position in the spray sheet measured with respect to the centerline of the splashplate. Hence, the MFF becomes the ratio of the mass flux into the box at angle ($\theta \pm 2\ \Delta\theta/2$) to the mass flux averaged over the spray angle, α.

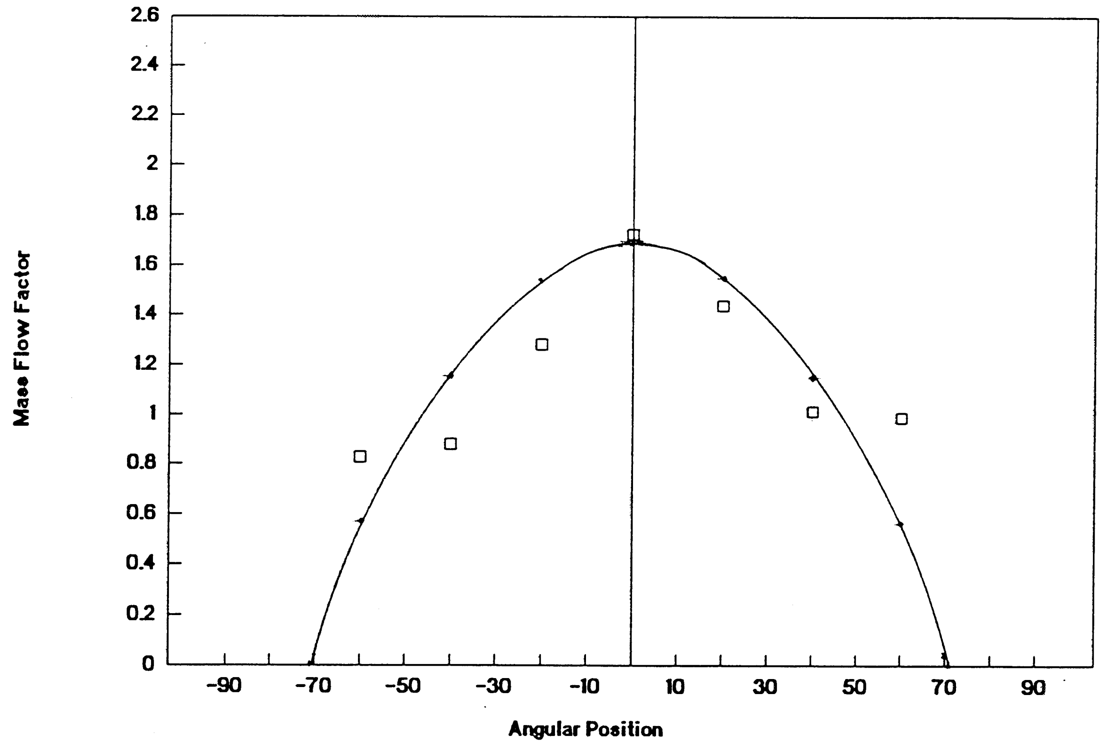

Fig. 4 - Mass Flow Distribution for Test 30A

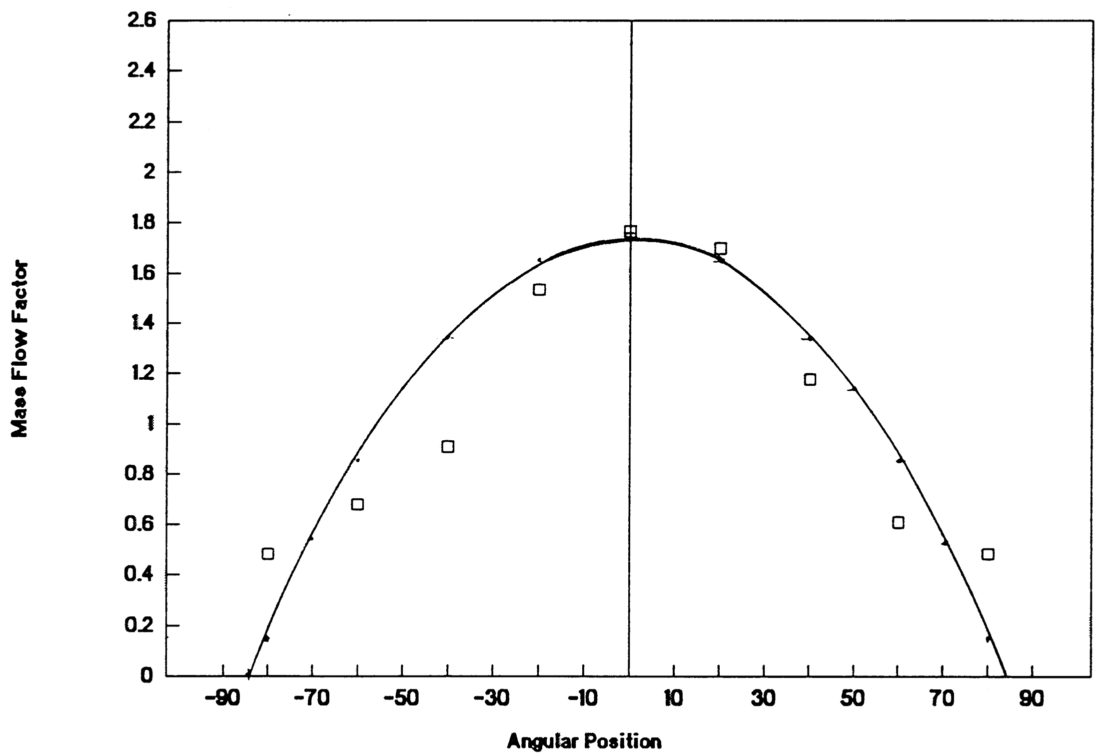

Fig. 5 - Mass Flow Distribution for Test 30B

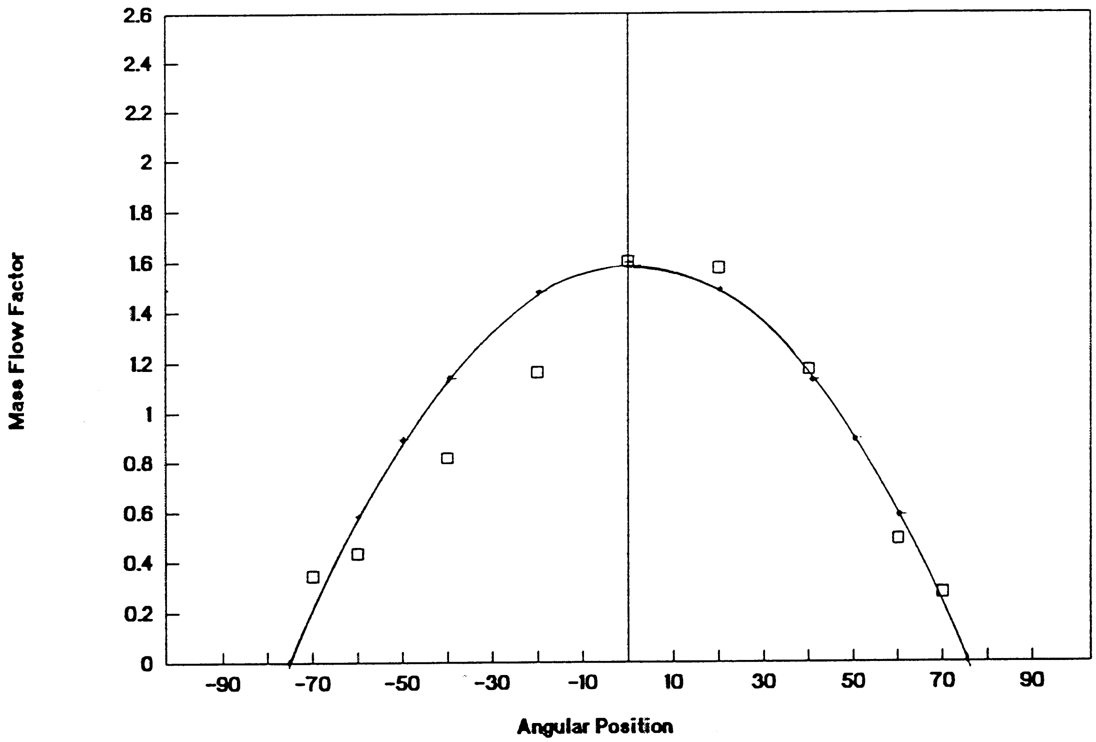

Fig. 6 - Mass Flow Distribution for Test 31A

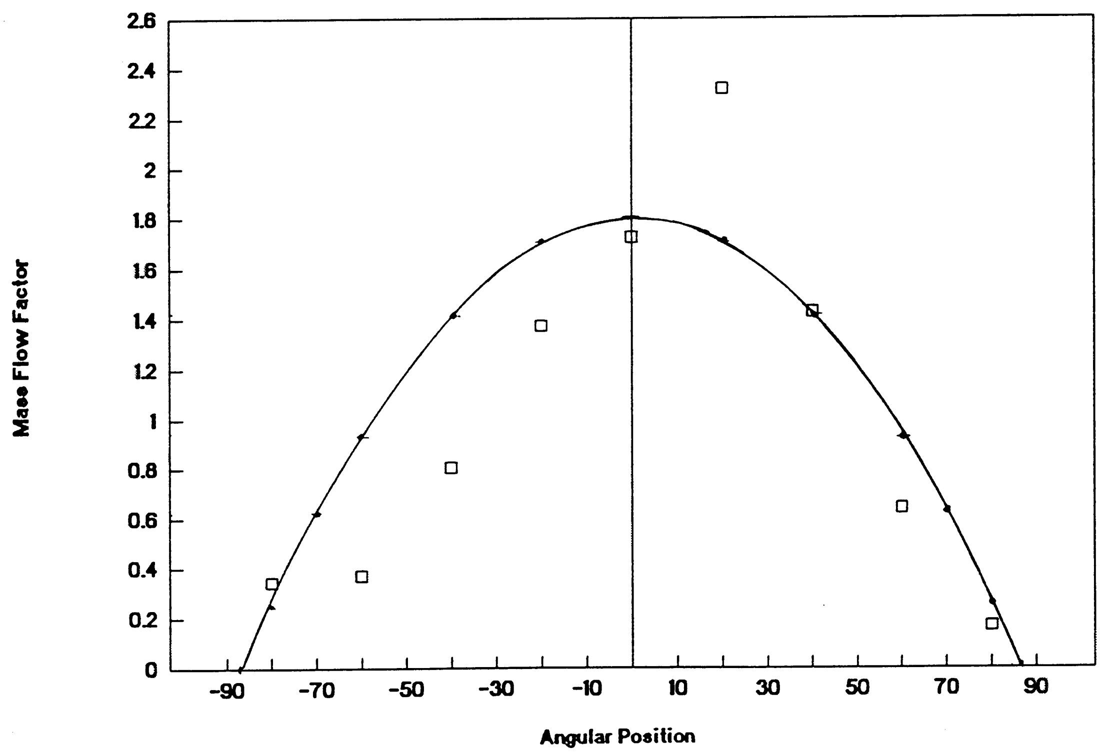

Fig. 7 - Mass Flow Distribution for Test 31B

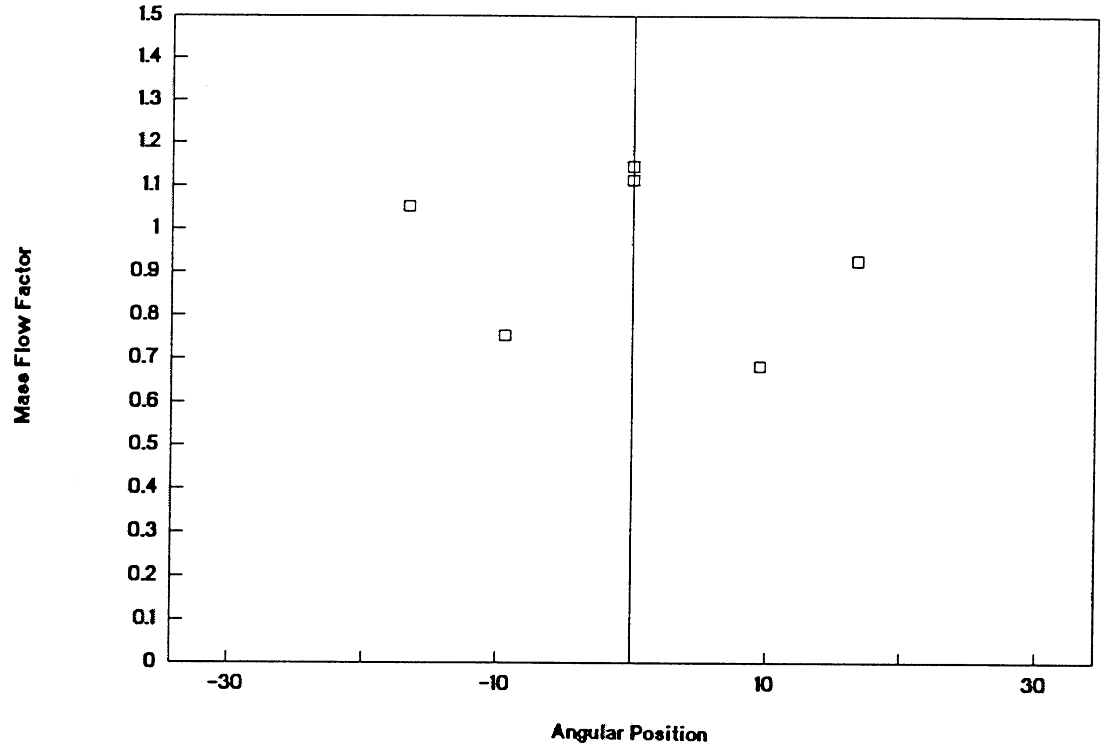

Fig. 8 - Mass Flow Distribution for Test 27A

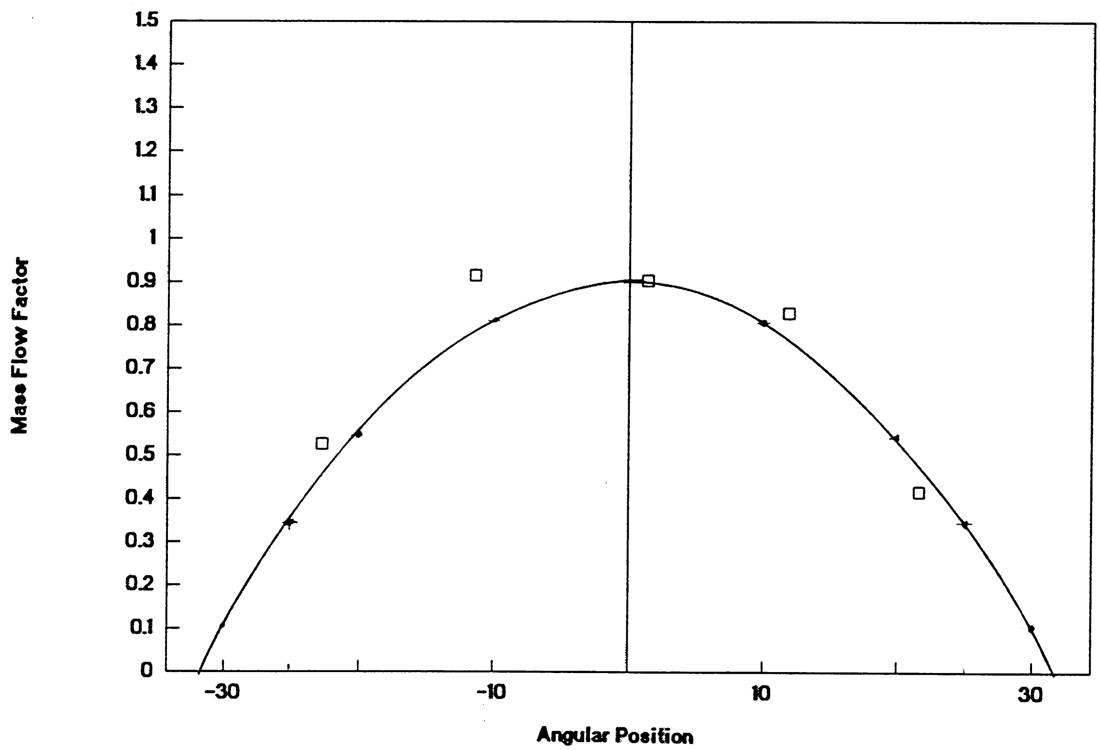

Fig. 9 - Mass Flow distribution for Test 28A

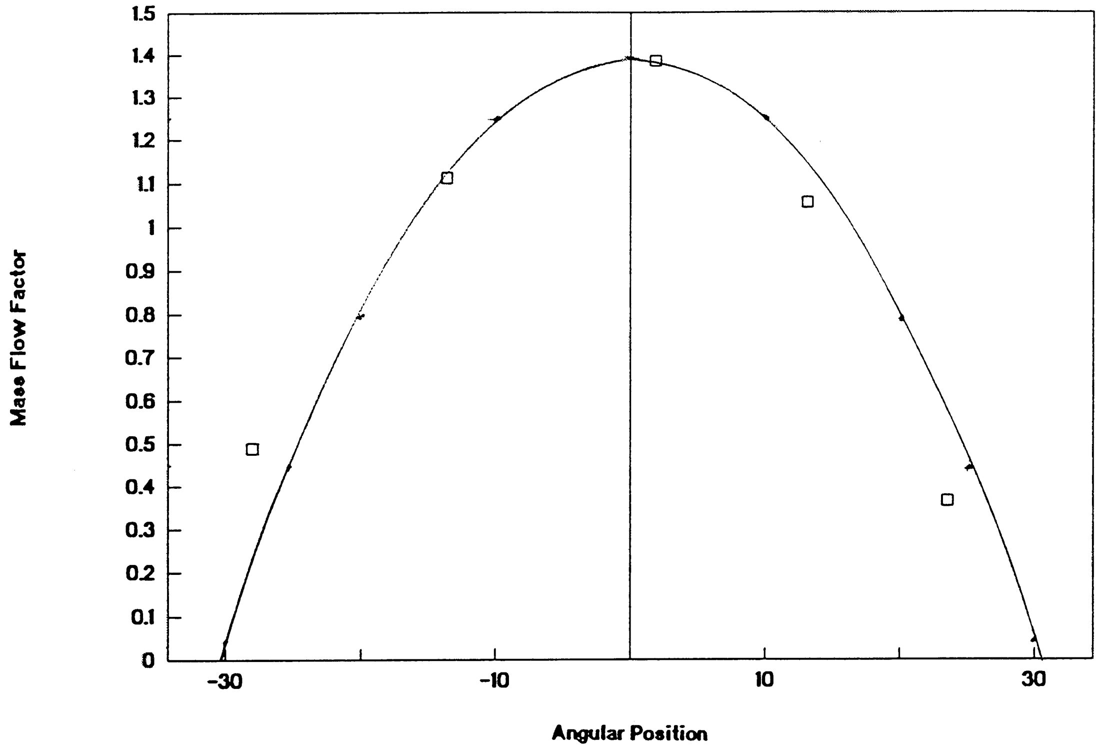

Fig. 10 - Mass Flow Distribution for Test 28B

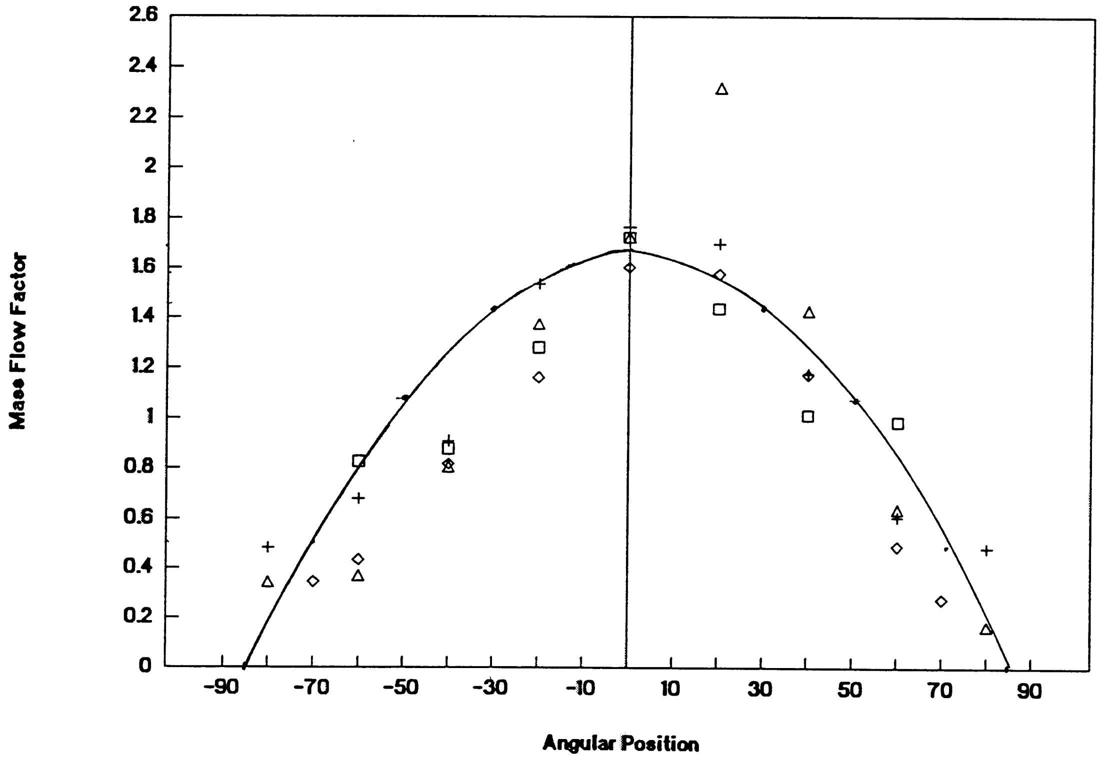

Fig. 11 - Mass Flow Distribution for Combined Splashplates

$$MFF = \frac{\Delta M/\Delta\theta}{M_o/\alpha} \quad (1)$$

where: ΔM = mass flow rate into sample box (g/s)
θ = position angle of sample box (°)
$\Delta\theta$ = angle subtended by sample box (°)
M_o = total liquor flow rate (g/s)
α = spray angle (°)

The MFF is plotted as a function of the position angle in Figs. 4-7 for the B&W splashplate nozzle. All four curves have a similar overall shape which does not appear to be strongly influenced by variations in viscosity or flow rate over the ranges tested. From visual observations, one could see that there was a central core in the angular range from $-15° < \theta < 15°$ having a relatively uniform flow rate. Outside this region, the flow rate dropped off steadily almost to the outer edge. At the very edge of the sheet, there was a thick rim. Hence, just inside the spray (half)angle, the MFF did not tail off, but beyond the spray (half)angle the mass flux abruptly dropped to zero.

Tests 31A and 31B showed unusually high flows at about +20° from the centerline. These high flows were relatively stable phenomena which remained in these sprays for several minutes and showed up consistently in the mass measurements at this location. The cause of this may be due to a secondary flow of black liquor which circulates around the tip of the nozzle and falls back on to the spray sheet. This secondary flow is always present with splashplate nozzles. It is created by backwards flow on the splashplate starting at the point of impingement, followed by flow around the recess that encircles the nozzle tip and by formation of a separate flow off the splashplate. The point where it contacts the sheet is a function of nozzle orientation. Unlike the video work done to determine drop size where the spray sheet is in a vertical plane, the mass flow measurements were made with the spray pattern in a horizontal orientation. The mass flow of this secondary stream was relatively small, but it appeared to have the effect of shifting the splashplate flow off to one side of the splashplate centerline, most likely because the splashplate was not exactly horizontal.

The spray patterns for the V-jet as shown in Figs. 8-10 were more sensitive to variations in the test conditions. At low viscosity and pressure (55 cP, 75 kPa), Fig. 9 shows the mass distribution to be close to plug flow over much of the spray angle. At a higher flow rate (68 cP, 137 kPa), not only did the spray angle increase (Fig. 10), but there was also a higher mass flow at the centerline and a steeper profile. At high viscosity (346 cP, 76 kPa), the mass distribution showed an unusual notched pattern (Fig. 8), apparently due to the formation of a thick outer rim and a thin region inside this rim.

An empirical correlation of MFF as a function of angular position (Θ) would be useful for predicting mass flow distribution for a nozzle under specified operating conditions. A regression analysis indicated that either a linear or a parabolic dependence would produce a reasonable estimate of the MFF profile. Although the linear correlation has the advantage of simplicity, the slope of the "curve" at $\Theta = 0$ has a discontinuity, whereas the experimental curve is rather flat in this region. The parabolic correlation satisfies this criterion at the centerline, and hence, it has been used to represent the data.

If the MFF is expressed in the form:

$$MFF = A - B\,\Theta^2 \tag{2}$$

the constants A and B can be approximated, knowing the MFF at $\Theta = 0$ and at some other angular position, $\Theta(1)$. Hence, at $\Theta = 0$, MFF = A; at $\Theta = \Theta(1)$, MFF = MFF(1), and $B = [A - MFF(1)]/\Theta(1)^2$. Results are shown in Table 2 and are represented by the curves in Figs. 4-7,9-11.

Table 2 - Constants for MFF Correlation

Run	MFF @ $\Theta = 0$	MFF @ $\Theta(1)$	$\Theta(1)$	A	B	α
30A	1.7	0.85	50	1.7	0.00034	157
30B	1.75	0.60	68	1.75	0.00025	190
31A	1.6	0.40	65	1.6	0.00028	160
31B	1.8	0.25	80	1.8	0.00024	200
Splashplate Composite	1.68	0.5	70	1.68	0.00024	184
28A	0.9	0.55	20	0.9	0.00088	-
28B	1.4	0.45	25	1.4	0.00152	56

In modeling the MFF as a parabolic function, it will be shown that the experimental constants, A and B, and the spray angle, α, are not all independent. In fact, experimentally determining A and B allows calculation of the expected spray angle, α. This is very desirable, since experimental values of α could not be determined exactly.

From eq.(1),

$$MFF = \frac{\Delta M/\Delta\Theta}{M_o/\alpha} = \frac{\rho\ v\ z\ R\ \Delta\Theta/\Delta\Theta}{\rho\ v_a\ z_a\ R\ \alpha/\alpha} = \frac{v\ z}{v_a\ z_a} \tag{3}$$

where: ρ = liquor density
v = liquor sheet velocity at angle Θ and distance R from the nozzle
v_a = average liquor sheet velocity
z = sheet thickness at angle Θ and distance R from nozzle
z_a = average sheet thickness at distance R from nozzle
R = radial distance from nozzle

Therefore:

$$\frac{v\ z}{v_a\ z_a} = A - B\ \Theta^2 \tag{4}$$

But

$$\rho\ v_n\ \pi\ D_n^2/4 = \rho\ v_a\ z_a\ R\ \alpha$$

$$v_a\ z_a = \frac{v_n\ \pi\ D_n^2}{4\ R\ \alpha} \tag{5}$$

where: v_n = liquor velocity at nozzle
D_n = nozzle diameter

Therefore:

$$v\ z\ R\ d\Theta = \frac{v_n\ \pi\ D_n^2}{4\ \alpha}\ (A - B\ \Theta^2)\ d\Theta \tag{6}$$

Integrating both sides of eq.(6) between the limits of $\pm\ \alpha/2$, the result is

$$A = 1 + B\ \alpha^2/12$$

or

$$\alpha = \pm\ (12(A-1)/B)^{1/2} \tag{7}$$

Values of α calculated from eq.(7) are listed in Table 2 and can be compared with the experimentally observed values for α listed in Table 1. The predicted values and are generally within 20% of each other.

Since the model defines the spray (half)angle as the angular position ($\pm\ \alpha/2$) where the product, v z, goes to zero, eq.(6) with $\Theta = \alpha/2$ reduces to:

$$0 = A - B(\alpha^2)/4$$

or

$$B = 4A/\alpha^2$$

and from eq.(7):

$$A = 1 + \frac{4\ A}{12} = 1.5$$

Hence, the model fundamentally predicts the MFF at $\theta = 0$ to be 1.5. Experimentally determined values generally fall within 20% of the theoretical value.

CONCLUSIONS

1. Measurements of the local distribution of black liquor flow in the spray pattern from sheet-forming nozzles were made as a function of the angle from the sheet centerline. Qualitative visual observations of the liquor sheets from both the splashplate and V-jet nozzles showed that there was a central core with a fairly uniform flow rate in the area within about 15° of the sheet centerline. Outside this region, the flow dropped off steadily almost to the outer edge of the sheet. At the very edge was a thick rim.

2. Modeling the mass flux profile as a parabolic function of angular position, with the flux exhibiting a maximum at the centerline and decreasing with increasing angular position, predicted the mass flux at the sheet centerline to be 1.5 times the average flux for the entire sheet cross section at the same radial distance from the tip of the nozzle. Model predictions of both the centerline flux and the full spray angle agreed to within 20% of the experimental values for the splashplate nozzle.

3. These results should provide key input to mathematical models of the combustion processes occurring in kraft recovery boilers.

LITERATURE

1. Green, R.P. and Hough, G. (eds.), Chemical Recovery in the Alkaline Pulping Processes (3rd ed.), p. 2, TAPPI Press, Atlanta (1992).

2. Hupa, M., Solin, P., and Hyoty, P., "Combustion Behavior of Black Liquor Droplets," Proc. Intl. Chem. Recov. Conf. (New Orleans), TAPPI/CPPA, 335-344 (1985).

3. Empie, H.J., Lien, S.J., Yang, W., Samuels, D.B., and Adams, T.N., "Kraft Black Liquor Delivery Systems Report No. 3," U.S. DOE Contract No. DE-FC02-88CE40839, IPST (December 1991).